

Ensemble Data Assimilation and Predictability of Tropical Cyclones

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LONG-TERM GOALS

The ultimate goal is to improve tropical cyclone track and intensity prediction through further development of ensemble-based data assimilation at the regional scale. More specifically, the objective is to make better use of in-situ and remotely-sensed observations in cloud-resolving models. In collaboration with scientists at the Naval Research Lab (NRL), we would like to develop an ensemble-based data assimilation system for the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) that is capable of assimilating remotely sensed data, as well as observations from conventional meteorological networks, to improve tropical cyclone prediction. This work will build upon a prototype COAMPS-based ensemble Kalman filter (COAMPS-EnKF) that has been recently developed at NRL following the success of the ensemble data assimilation system developed at the Pennsylvania State University (PSU) for the Weather Research and Forecasting (WRF) model.

OBJECTIVES

The primarily objectives of the proposed work are as follows:

- (1) Further develop the COAMPS-EnKF data assimilation system for tropical cyclone initialization capable of effectively assimilating airborne Doppler radar and satellite observations as well as data from conventional surface and sounding networks.
- (2) Implement a pseudo ensemble data assimilation (PEDA) system for COAMPS that is capable of ingesting flow-dependent background error covariance for tropical cyclone initialization without performing a computationally expensive online ensemble forecast. PEDa operates by sampling from a pre-constructed TC vortex library, given the intensity and size of the observed storm, and introducing the sample perturbations into a variational data assimilation system. For this task, the PEDa algorithm will be implemented with the COAMPS three-/four-dimensional variational (3D-/4D-Var) hybrid systems.
- (3) Explore the practical use of different observing strategies in predicting tropical cyclones, including the assimilation of dropsondes, radar, airborne and spaceborne observations using the COAMPS-EnKF and COAMPS-PEDA systems.

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- (4) Develop quality control and data thinning procedures for COAMPS-EnKF by implementing successful strategies from the pre-existing PSU WRF-based EnKF data assimilation system (WRF-EnKF).

APPROACH

Since the beginning of this project renewal on 1 February 2012, two doctoral students (Jonathan Poterjoy and Christopher Melhauser) have been dedicated to the project tasks at the Pennsylvania State University under the guidance of both PI's (Drs. Fuqing Zhang and Yonghui Weng) and NRL collaborators Dr. Allen Zhao and Jim Doyle. As a continuation of the previous ONR funding, Mr. Poterjoy focuses on the structure and sampling errors in tropical cyclone background error covariance, and its implications for ensemble data assimilation. His current work uses the WRF-EnKF framework, but the findings are transferable to the COAMPS-EnKF system that is being developed. He is also working on comparing and coupling the ensemble and variational data assimilation methods for tropical cyclone applications. Mr. Melhauser, who started to work on the project early this summer, has successfully implemented COAMPS in the PSU computing environment. With some delays in the approval process, we have now successfully received the prototype COAMPS-EnKF code from NRL where it was originally developed.

We are also actively collaborating with Drs. Allen Zhang and Dr. Jim Doyle as well as other scientists at NRL to implement COAMPS and COAMPS-EnKF. We will soon begin to further develop the COMAPS-EnKF data assimilation by transferring some capabilities from the WRF-EnKF system, and test the upgraded COAMPS software.

We have continued our real-time ensemble analysis and prediction of Atlantic tropical cyclones through 2012, assimilating airborne Doppler radar observations at a cloud-resolving model resolution. This work continues through collaboration with scientists who participate in the NASA Hurricane and Severe Storm Sentinel (HS3) field campaign using Global Hawk, and the NOAA Hurricane Forecast Improvement Project (HFIP). In the meantime, we are continuing our development of a pseudo-hybrid ensemble data assimilation (PEDA) system that is capable of assimilation inner-core observations with vortex-dependent error covariance without an online cloud-resolving ensemble; PEDa will be tested in the COAMPS modeling system in the near future. Through ensemble simulations and sensitivity experiments, we will continue to examine the flow- and regime- dependent predictability of tropical cyclones.

WORK COMPLETED

As a continuation and expansion of the PI's past ONR project that ended in 2011, we have made significant progress in improving our understanding of tropical cyclone predictability and further developed ensemble-based data assimilation methods for tropical cyclones. Now that we have successfully installed the prototype COAMPS-EnKF on the PSU computing cluster, our ongoing focus will be on the development of the new system, and its application for studying the dynamics and predictability of tropical cyclones, along with determining affective observing strategies. The following tasks have been completed:

- 1) Successfully compile COAMPS v3.1.1 and v4.2.2 on the local PSU cluster

- 2) Successfully execute COAMPS v3.1.1 “bench” test and COAMPS v4.2.2 “newbench” test
- 3) Download NOGAPS and observation data from the GODAE server for Hurricane Karl (2010) and execute a full multi-domain analysis and model forecast
- 4) Successfully compile and execute COAMPS Utilities on the PSU cluster
- 5) Successfully compile and execute the NRL “getgfs” code to convert GFS 1° and 0.5° model output into NOGAPS data for COAMPS initial and boundary conditions
- 6) Successfully execute COAMPS v4.2.2 utilizing GFS initial and boundary conditions for Hurricane Karl (2010) utilizing observations and sea surface data (ghrsst) from GODAE
- 7) Successfully compile the COAMPS-EnKF system on the local PSU cluster

RESULTS

Highlights of the work completed over the past year since the start of the renewal project are listed below.

- (1) *Mesoscale dynamics and predictability of tropical cyclones and hurricanes (Stern and Zhang 2012a,b; Xie and Zhang 2012; Xie et al. 2012; Zhang and Tao 2012; Munsell et al. 2012; Fang and Zhang 2012; Melhauser et al. 2012)*: The use of probabilistic methods and ensemble analysis to investigate the genesis dynamics and predictability of Tropical Storm Erika (2009), Hurricane Karl (2010), Typhoon Morakot (2009), Super Typhoon Megi (2010) during ITOP, as well as through ensemble simulations of idealized tropical cyclones with and without wind shear. It is found that at least for some cases, the predictability of tropical cyclones may be limited by the randomness of moist convection and the uncertainties in representing features of the larger-scale environment, including the environmental wind shear and moisture distribution.
- (2) *Improve tropical cyclone track and intensity prediction through further development of the regional-scale, cloud-resolving ensemble-based data assimilation and prediction system capable of efficiently assimilating ground-based and airborne Doppler and to examine the efficiency of observation targeting (Poterjoy et al. 2012; Weng and Zhang 2012; Green and Zhang 2012; Sippel et al. 2012; Aksoy et al. 2012; Jung et al. 2012)*. We examined the performance of the ensemble-based data assimilation and prediction system with Doppler radar observations systematically for all the 2008-2011 storms that had airborne Doppler missions. We also began including the HIWRAP airborne Doppler observations from Global Hawk into the set of observations to be assimilated. Our findings show that ensemble analyses and forecasts that include Doppler wind observations can notably improve the track and intensity prediction while revealing significant uncertainty in the forecast.
- (3) *Intercomparison and hybrid of ensemble with variation method (Zhang and Zhang 2012; Zhang et al. 2012a,b)*. We have performed by far the most extensive comparison of 3DVar, 4DVar, EnKF, and EnKF-3DVAR and EnKF-4DVAR hybrids at the regional scale, demonstrating clear benefits of the hybrid approaches. The pseudo-hybrid ensemble data assimilation (PEDA) system we developed is capable of assimilating inner-core observations with vortex-dependent error covariance without an online cloud-resolving ensemble.
- (4) *Transferring the COAMPS and its EnKF software to PSU computing environment*: The prototype COAMPS-EnKF code developed by Dr. Allen Zhao at NRL was based on the WRF-EnKF, a system

developed by the PI that is capable of assimilating in-situ and remotely-sensed observations including radar data. While the PI's team at PSU finally has the approval to use the COAMPS-EnKF data assimilation system, we have begun to focus on the upgrade stage of this project.

IMPACT/APPLICATIONS

Understanding the limit of tropical cyclone predictability and the associated error growth dynamics is essential for setting up expectations and priorities for advancing deterministic forecasting and for providing guidance on the design, implementation and application of short-range ensemble prediction systems. Understanding the nature of tropical cyclone predictability is also crucial to the design of efficient data assimilation systems for tropical cyclones. Advanced ensemble-based data assimilation systems that are capable of assimilating both Doppler radar and satellite observations are very promising for the future cloud-resolving ensemble prediction of tropical cyclones.

TRANSITIONS

In collaborations with scientists at NRL in Monterey, the WRF-based ensemble data assimilation system that is partially sponsored by this project is currently being transferred to the Navy mesoscale prediction model, COAMPS, with the potential to be used in future operational forecasts.

The ensemble-based data assimilation system is also currently being used for quasi-operational hurricane prediction system as part of the NOAA's stream-1.5 runs of the Hurricane Forecast Improvement Project.

The ensemble-based data assimilation system is also being used by NASA scientists for assimilating HIWRAP airborne Doppler radar observations from Global Hawk for the GRIB/HS3 program.

PUBLICATIONS THIS YEAR (fully or partially funded by this grant) ("*" student or postdoc)

1. Zhang*, M. and F. Zhang, 2012: E4DVar: Coupling an ensemble Kalman filter with four-dimensional variational data assimilation in a limited-area weather prediction model. *Monthly Weather Review*, 140, 587-600.
2. Weng*, Y. and F. Zhang, 2012: Assimilating Airborne Doppler Radar Observations with an Ensemble Kalman Filter for Cloud-resolving Hurricane Initialization and Prediction: Katrina (2005). *Monthly Weather Review*, 140, 841-859.
3. Jung, B.-J., H.-M. Kim, F. Zhang and C.-C. Wu, 2012: Effect of targeted dropsonde observations and best track data on the track forecasts of Typhoon Sinlaku (2008) using an Ensemble Kalman Filter. *Tellus A*, 64, 14984.
4. Montgomery, M. T., C. Davis, T. Dunkerton, Z. Wang, C. Velden, R. Torn, S. Majumdar, F. Zhang, R. K. Smith, L. Bosart, M. M. Bell, J. S. Haase, A. Heymsfield, and M. A. Boothe, 2012: The Pre-Depression Investigation of Cloud Systems in the Tropics (PREDICT) experiment: Scientific basis, new analysis tools and some first results. *Bulletin of the American Meteorological Society*, 93, 152-172.
5. Aksoy, A., S. Lorsolo, T. Vukicevic, K. J. Sellwood, S. D. Aberson, and F. Zhang, 2012: NOAA/AOML/HRD's HWRF ensemble data assimilation system (HEDAS) for the assimilation of high-resolution hurricane inner-core data: Impact of airborne Doppler radar

- observations in an OSSE. *Monthly Weather Review*, 140, 1843–1862. doi: <http://dx.doi.org/10.1175/MWR-D-11-00212.1>.
6. Rozoff, C. M., D. S. Nolan, J. P. Kossin, F. Zhang, and J. Fang, 2012: The roles of an expanding wind field and inertial stability in tropical cyclone secondary eyewall formation. *Journal of the Atmospheric Sciences*, 69, 2621–2643. doi: <http://dx.doi.org/10.1175/JAS-D-11-0326.1>
 7. Fang*, J. and F. Zhang, 2012: Beta effect on the development of tropical cyclones. *Monthly Weather Review*, 140, 3327–3346. doi: <http://dx.doi.org/10.1175/MWR-D-10-05021.1>.
 8. Xie*, B and F. Zhang, 2012: Impacts of typhoon track, island topography and monsoon flow on the heavy rainfalls in Taiwan associated with Morakot (2009). *Monthly Weather Review*, 140, 3379–3394.
 9. Zhang, F., M. Zhang*, J. Poterjoy*, 2012a: E3DVar: Coupling an ensemble Kalman filter with three-dimensional variational data assimilation in a limited-area weather prediction model and comparison to E4DVar. *Monthly Weather Review*, in press. doi: <http://dx.doi.org/10.1175/MWR-D-12-00075.1>
 10. Stern*, D. P. and F. Zhang, 2012: How does the eye warm? Part I: A potential temperature budget analysis of an idealized tropical cyclone. *Journal of the Atmospheric Sciences*, in press. doi: <http://dx.doi.org/10.1175/JAS-D-11-0329.1>
 11. Zhang, F., and D. Tao*, 2012: Impacts of vertical wind shear on the predictability of tropical cyclones. *Journal of the Atmospheric Sciences*, accepted.
 12. Xie*, B. and F. Zhang, Q. Zhang, J. Poterjoy* and Y. Weng*, 2012: Observing Strategy and Observation Targeting for Tropical Cyclones using Ensemble-based Sensitivity Analysis and Data Assimilation. *Monthly Weather Review*, accepted.
 13. Sippel, J. A., S. A Braun, F. Zhang, Y. Weng*, 2012: Ensemble Kalman Filter Assimilation of Simulated HIWRAP Doppler Velocity Data from a Hurricane. *Monthly Weather Review*, accepted subjected to minor revisions.
 14. Zhang, F., X. Ge, Y. Weng and J. Poterjoy, 2012b: PEDA: a pseudo ensemble hybrid data assimilation system for tropical cyclone initialization. *Advances in Atmospheric Sciences*, accepted subjected to revisions.
 15. Munsell*, E.B., F. Zhang, and D.P. Stern*, 2012: Predictability and dynamics of a non-intensifying tropical storm: Erika (2009). *Journal of the Atmospheric Sciences*, submitted.
 16. Jin, Y., W. Thompson, M. DeMaria; F. Zhang, M. Peng; M. Powell, F. Marks and P. Black, 2012: Observations and modeling of landfalling tropical cyclones. *Bulletin of the American Meteorological Society*, submitted.
 17. Green*, B.W. and F. Zhang, 2012: Impacts of air-sea flux parameterizations on the intensity and structure of tropical cyclones. *Monthly Weather Review*, submitted.
 18. Stern*, D. P. and F. Zhang, 2012: How does the eye warm? Part II: Sensitivity to Vertical Wind Shear, and a Trajectory Analysis. *Journal of the Atmospheric Sciences*, submitted.
 19. Poterjoy*, J., F. Zhang and Y. Weng*, 2012: The effects of sampling error on the EnKF assimilation of inner-core hurricane observations. *Monthly Weather Review*, in preparation with completed draft.

20. Melhauser*, C. and F. Zhang, 2012: The impacts of radiation and diurnal cycle on the development of Hurricane Karl (2010). *Geophysical Research Letters*, in preparation.